Reexamination of the Galaxy Formation-Regulated Gas Evolution Model in Groups and Clusters

Xiang-Ping Wu and Yan-Jie Xue

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012; China

ABSTRACT

As an alternative explanation of the entropy excess and the steepening of the X-ray luminosity-temperature relation in groups and clusters, the galaxy formation-regulated gas evolution (GG) model proposed recently by Bryan makes an attempt to incorporate the formation of galaxies into the evolution of gas without additional heating by nongravitational processes. This seems to provide a unified scheme for our understanding of the structures and evolution of both galaxies and gas in groups and clusters. In this paper, we present an extensive comparison of the X-ray properties of groups and clusters predicted by the GG model and those revealed by current X-ray observations, using various large data sources in the literature and also taking the observational selection effects into account. These include an independent check of the fundamental working hypothesis of the GG model, i.e., galaxy formation was less efficient in rich clusters than in groups, a new test of the radial gas distributions revealed by both the gas mass fraction and the X-ray surface brightness profiles, and an reexamination of the X-ray luminosity-temperature and entropy-temperature relations. In particular, it shows that the overall X-ray surface brightness profiles predicted by the GG model are very similar in shape, insensitive to the X-ray temperature, and the shallower X-ray surface brightness profiles seen at low-temperature systems may arise from the current observational selection effect. This can be used as the simplest approach to distinguishing between the GG model and the preheating scenario. The latter yields an intrinsically shallower gas distribution in groups than in rich clusters.

Subject headings: cosmology: theory — galaxies: clusters: general — X-ray: general

1.   Introduction

It has been realized for a decade that the ratio of gas mass to stellar mass in groups and clusters of galaxies is positively correlated with the X-ray gas temperature. This suggests a simple scenario in which galaxy formation was more efficient in groups than in clusters (David et al. 1990). As a consequence, the stellar (gas) mass fraction should decrease (increase) from groups to clusters, resulting in the increasing mass-to-light ratio and X-ray luminosity with X-ray temperature. It seems that these predictions have been well justified by the optical measurements of the mass-to-light ratios (e.g. Girardi et al. 2000) and the X-ray determinations of the gas fractions in clusters (e.g. Mohr, Mathiesen & Evrard 1999; MME), and in particular by the discovery of the steepening of the X-ray luminosity (L_x)-temperature (T) relation for groups and clusters (Henry & Arnaud 1991; Edge & Stewart 1991; David et al. 1993; Wu, Xue & Fang 1999; Xue & Wu 2000 and references therein). Nevertheless, despite these apparent successes, such a simple scenario has received less attention over the past years than the prevailing 'preheating' hypothesis. The latter assumes that the gas was preheated by nongravitational processes such as supernovae and AGNs before collapsing into groups and clusters, which raises the gas entropy and makes the warm/hot gas harder to compress (Kaiser 1991). Indeed, the nongravitational heating mechanism can significantly reduce the gas content bound within the virial radii of groups and poor clusters, providing a satisfactory explanation of the observational facts listed above (e.g. Cavaliere, Menci & Tozzi 1997; 1999; Bower et al. 2001). In particular, the subsequent detection of the entropy excess in the centers of groups and clusters by Ponman, Cannon & Navarro (1999) seems to give a convincing support to the preheating hypothesis. Yet, the main difficulty with the preheating model is the unreasonably high efficiency of energy injection into the intragroup/intracluster gas from supernovae (Wu, Fabian & Nulsen 2000; Bower et al. 2001), although additional heating from AGNs might help to alleviate the discrepancy. Furthermore, a uniform preheating of the cosmic baryons to a

temperature of $\sim 10^6$ at high redshifts may make the Lyα forest ($T \sim 10^4$ K) to disappear.

By inheriting the observational evidence that the efficiency of galaxy formation was higher in groups than in clusters, Bryan (2000) proposed that the lowest entropy gas in groups and clusters should be responsible for the formation of stars. Namely, the gas in the central regions of groups and clusters was converted into stars in the early phase of structure formation, and the central gas cavity was refilled with the remaining gas distributed originally at large radii. This latter process brought the higher entropy gas inward and thus raised the central entropy of the gas, providing an alternative explanation of the existence of the entropy floor in the centers of groups and clusters reported by Ponman et al. (1999). The most important issue behind this simple scenario, we believe, is that the distribution and evolution of the gas are incorporated with the formation of the galaxies so that the optical/X-ray properties of the gas and galaxies in groups and clusters can be naturally explained within a unified scheme and without invoking additional heating processes. This galaxy formation-regulated gas evolution (GG) model in groups and clusters has several unambiguous predictions that can be easily tested with current available data or future observations. For example, (1)while the stellar and gas mass fractions vary from groups to clusters, the total baryon (stellar mass + gas mass) fraction in any group or cluster remains a universal value; (2)The mass-to-light ratio is an increasing function of X-ray temperature; (3)Less massive systems (e.g. groups) contain less gas and hence have lower X-ray emission, which is the key issue for the reproductions of the observed L_x-T relation and entropy distribution; (4)Radial profile of the stellar mass fraction should demonstrate a decreasing trend towards large radii, and an opposite situation occurs for that of the gas mass fraction. Of course, whether or not these properties are in quantitative agreement with observations deserves further investigation.

In the pioneering work of Bryan (2000), an overall agreement between the predicted

and observed L_{x}-T relations and entropy distributions has been essentially found, although at low temperature $T < 1$ keV, the observed L_{x}-T relation falls below the theoretical prediction. Motivated by these successes and their profound implications for our understanding of the formation and evolution of the galaxies and gas in groups and clusters, we wish to conduct an extensive comparison of the theoretically predicted properties of the intragroup/intracluster gas by the GG model with those revealed by current X-ray observations. These include not only the global dependence of the X-ray luminosity, entropy and gas fraction upon the X-ray temperature T, but also the internal structures of the intragroup/intracluster gas such as the radial distribution of gas fraction, the X-ray surface brightness profile (slope and core radius parameters), etc. Moreover, some selection effects of current X-ray observations (e.g. the finite extensions of X-ray surface brightness profiles due to background noise, the spectral fitting temperature, etc.) will be taken into account. It is hoped that our comparison would be useful for an eventually conclusive test of the GG model. Throughout this paper we assume a flat cosmological model (ΛCDM) of $\Omega_{\mathrm{M}} = 0.3$, $\Omega_{\Lambda} = 0.7$ and $h = 0.65$.

2. The Model

2.1. Reexamination of the working hypothesis

We begin with a reexamination of the fundamental relationship between the stellar mass fraction f_{star} and X-ray temperature T of groups and clusters. Based on three independent studies of 33 groups and clusters in the literature, Bryan (2000) derived the following empirical formula, regardless of the large scatter of the data points especially for low-temperature groups,

$$f_{\mathrm{star}} = (0.042 \pm 0.003) \left(\frac{kT}{10 \text{ keV}} \right)^{-0.35 \pm 0.06}, \tag{1}$$

where the quoted errors are 68% confidence limits. The lack of a large sample of optical/X-ray groups and clusters in which both stellar mass and gas mass are reliably determined out to virial radii r_{vir} hinders us from directly reexamining the validity of this relation. Nevertheless, there exist several indirect ways that may allow us to test the consistency between equation (1) and other independent measurements.

The GG model admits the universality of the baryon fraction f_b in different groups and clusters: $f_b = f_{\mathrm{star}} + f_{\mathrm{gas}}$. For the ΛCDM model and $\Omega_b = 0.020h^{-2}$, we have $f_b = 0.16$. Therefore, the measurement of the gas fraction f_{gas} in different groups and clusters permits an indirect test of the dependence of the stellar mass fraction upon the X-ray temperature. The major difficulty of this exercise is the determination of total group/cluster mass M_{vir}, in which one often needs to extrapolate the available X-ray data within finite detection aperture to virial radii r_{vir}, along with the assumption of hydrostatic equilibrium. Such an extrapolation may be safely applicable only to X-ray luminous and rich clusters. For this reason, we extract a sample of 45 nearby ($z < 0.1$), X-ray luminous clusters from MME and Ettori & Fabian (1999; EF). The restriction on cluster redshifts is consistent with the three samples used by Bryan (2000), and also gets rid of the influence of cosmological parameters other than the Hubble constant. These authors have explicitly derived the gas fraction within r_{500} where the overdensity Δ of the cluster dark matter with respect to the critical density of the universe is $\Delta = 500$. r_{500} can be approximately regarded as the virial radius if we notice that the asymptotic gas fractions of rich clusters at large radii remain roughly constant for the conventional isothermal β model with $\beta = 2/3$, although the virial radius of a dynamically-relaxed system in the ΛCDM model corresponds to $\Delta \approx 100$. We display in Figure 1 the observationally determined gas fraction and the expectation of $f_{\mathrm{gas}} = 0.16 - 0.042(kT/10 \text{ keV})^{-0.35}$ from the empirical formula equation (1) by Bryan (2000). It is apparent that the two results are essentially consistent with each other.

EDITOR: PLACE FIGURE 1 HERE.

Another independent check of equation (1) is to examine the dependence of the mass-to-light ratio M/L upon the X-ray temperature. It follows that the mass-to-light ratio M/L can be rewritten as $M/L = (M/M_{\text{star}})(M_{\text{star}}/L) = \Upsilon f_{\text{star}}^{-1}$, where M_{star} is the total stellar mass of groups/clusters and $\Upsilon \equiv M_{\text{star}}/L$, while observations suggest that $\Upsilon \approx 6.5 \Upsilon_{\odot}$ for the dominant population of galaxies in clusters, ellipticals (see Fukugita, Hogan & Peebles 1998). As a result, the mass-to-light ratio should increase with the X-ray temperature according to equation (1). Now, instead of examining the dependence of M/L upon T, we would like to derive the f_{star}-T relation using the best-fit relation between cluster virial mass and optical luminosity found by Girardi et al. (2000):

$$\left(\frac{M_{\text{vir}}}{M_{\odot} h^{-1}} \right) = 10^c \left(\frac{L}{L_{\odot} h^{-2}} \right)^d , \tag{2}$$

where $c = -1.41$ and $d = 1.32$ for the fore/background correction based on mean galaxy counts. This yields

$$f_{\text{star}} = 10^{-c/d} \left(\frac{\Upsilon}{h \Upsilon_{\odot}} \right) \left(\frac{M_{\text{vir}}}{h^{-1} M_{\odot}} \right)^{-1+1/d} . \tag{3}$$

Employing the cosmic virial theorem at $z = 0$ (e.g. Bryan & Norman 1998)

$$\left(\frac{M_{\text{vir}}}{10^{15} M_{\odot}} \right) = \frac{1}{h \sqrt{\Delta}} \left(\frac{kT}{1.39 \text{ keV}} \right)^{3/2} , \tag{4}$$

we have

$$f_{\text{star}} = \left(1.93 \times 10^{16} \right)^{-1+1/d} 10^{-c/d} \Delta^{(1-1/d)/2} \left(\frac{\Upsilon}{h \, \Upsilon_{\odot}} \right) \left(\frac{kT}{10 \text{ keV}} \right)^{3(-1+1/d)/2} . \tag{5}$$

Finally,

$$f_{\text{star}} = 0.025 \left(\frac{kT}{10 \text{ keV}} \right)^{-0.36} , \tag{6}$$

in which we have adopted $\Upsilon = 6.5 \Upsilon_{\odot}$ and $\Delta = 200$. Actually, one can arrive at the essentially same conclusion using the empirical M_{vir}-T relationship for clusters instead of

the cosmic virial theorem equation (4). For example, the best-fit M_{200}-T relation based on the spatially resolved temperature profiles in the estimates of X-ray cluster masses given by Horner, Mushotzky & Scharf (1999) is

$$M_{200} = 8.2 \times 10^{14} \ M_{\odot} \ \left(\frac{kT}{10 \ \mathrm{keV}} \right)^{1.48}. \tag{7}$$

This yields, when combined with equation (3),

$$f_{\mathrm{star}} = 0.028 \left(\frac{kT}{10 \ \mathrm{keV}} \right)^{-0.36}. \tag{8}$$

Except the slightly lower amplitudes, both equations (6) and (8) are consistent with equation (1) especially when the large uncertainties in the fitting results [equations (1), (2) and (7)] are considered. In Figure 1 we illustrate the resulting gas fraction $f_{\mathrm{gas}} = 0.16 - f_{\mathrm{star}}$ using the stellar mass fraction of equation (6). It turns out that the derived gas fraction of rich clusters from f_{star} roughly agrees with that determined from the X-ray observations.

2.2.   Basic equations

The dark matter distributions in groups and clusters are assumed to be unaffected by the formation of galaxies and follow the universal density profile (Navarro, Frenk & White 1995; NFW):

$$\rho_{\mathrm{DM}}(r) = \frac{\delta_{\mathrm{crit}} \rho_{\mathrm{crit}}}{(r/r_s)(1 + r/r_s)^2}, \tag{9}$$

where δ_{crit} and r_s are the characteristic density and length, respectively, and ρ_{crit} is the critical density of the universe. The virial mass is defined as $M_{\mathrm{vir}} = 4\pi r_{\mathrm{vir}}^3 \Delta \rho_{\mathrm{crit}}/3$, and related to the virial temperature T_{vir} through the cosmic virial theorem equation (4). Following Bryan (2000), we adopt the fitting formula of the M_{vir}-c relation suggested by numerical simulations: $c = 8.5(M_{\mathrm{vir}} h/10^{15} \ M_{\odot})^{-0.086}$, where $c = r_{\mathrm{vir}}/r_s$ is the concentration parameter. Since the temperature in all the empirical formulae including the f_{star}-T

relation is the so-called spectral temperature T_{s} rather than the virial temperature T_{vir}, an appropriate connection between T_{s} and T_{vir} should be established in order to make a meaningful comparison to observations. Using hydrodynamic cluster simulations, Mathiesen & Evrard (2001) have recently conducted an extensive comparison of different measures of the intracluster gas temperature including the spectral temperature, the emission-weighted temperature and the mass-weighted (virial) temperature. In particular, it has been shown that T_{s} is generally lower than T_{vir} for clusters, depending on the bandpass used for spectral fitting. We adopt the best-fit relation between T_{s} and T_{vir} in the 2.0-9.5 keV band to proceed our numerical computation: $T_{\mathrm{vir}} = 0.91T_{\mathrm{s}}^{1.10}$. We have also tested another fitting formula in the 0.5-9.5 keV band, $T_{\mathrm{vir}} = 1.17T_{\mathrm{s}}^{1.00}$, and found that our main theoretical predictions remain unchanged. We will omit the subscript 's' in the spectral temperature. Whenever our theoretical predictions are compared with X-ray observations, we always work with the spectral fitting temperature.

For simplicity, we assume that the gas is dissipationless before galaxy formation so that the gas traces the underlying dark matter distribution and satisfies the equation of hydrostatic equilibrium

$$\frac{dP^0}{dr} = -\rho_{\mathrm{gas}}^0(r)\frac{GM_{DM}(r)}{r^2};\tag{10}$$

$$\rho_{\mathrm{gas}}^0(r) = f_b\rho_{\mathrm{DM}}(r).\tag{11}$$

We use the superscript '0' to denote the quantities before the formation of galaxies in the system. The temperature profile can be obtained by straightforwardly solving the above equations with the boundary restriction $T^0(r \to \infty) \to 0$:

$$kT^0(r) = kT^* \frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2 \int_{r/r_s}^{\infty} \frac{(1+x)\ln(1+x) - x}{x^3(1+x)^3}dx,\tag{12}$$

where $kT^* = 4\pi G\mu m_p\delta_c\rho_{\mathrm{crit}}r_s^2$ and $\mu = 0.59$ is the mean molecular weight. Note that unlike Bryan (2000), we did not choose the pressure-free external boundary condition $P^0 = 0$, i.e.

$T^0 = 0$ at $r = r_{\text{vir}}$, which would lead the entropy distribution $S^0 = \ln T^0/(n_e^0)^{2/3}$ to turn over near the boundary. While our boundary restriction $T^0(r \to \infty) \to 0$ seems to be more natural, the validity of equation (10) beyond r_{vir} becomes questionable. In this regard, our requirement of $T^0(r \to \infty) \to 0$ should not be taken too literally, and the key point here is that $T^0(r)$ should be a decreasing function of radius near r_{vir} and tend towards zero when $r \gg r_{\text{vir}}$.

Galaxy formation is equivalent to removing the central region of radius r_0 an amount of gas to $M_{\text{star}} = f_{\text{star}} M_{\text{vir}}$:

$$M^0_{\text{gas}}(r_0) = 0.042 \left(\frac{kT}{10\ \text{keV}} \right)^{-0.35} M_{\text{vir}}. \tag{13}$$

The remaining gas is redistributed by the conservation of gas mass

$$\int_{r_0}^{\bar{r}} 4\pi \mu_e m_p n_e^0(x) x^2 dx = \int_0^r 4\pi \mu_e m_p n_e(x) x^2 dx, \tag{14}$$

where $\mu_e = 2/(1 + X)$, and $X = 0.768$ is the hydrogen mass fraction in the primordial abundances of hydrogen and helium. Namely, the central region of radius r is refilled with the gas which is originally distributed at larger radii between r_0 and $\bar{r}$. This process transports the gas at $\bar{r}$ with entropy $S^0(\bar{r}) = \ln T^0(\bar{r})/[n_e^0(\bar{r})]^{2/3}$ to a new position r by the conservation of entropy

$$\frac{T(r)}{[n_e(r)]^{2/3}} = \frac{T^0(\bar{r})}{[n_e^0(\bar{r})]^{2/3}}. \tag{15}$$

The original position $\bar{r}$ can be thus fixed by combining the above two equations. Eventually, the saturated configuration should satisfy the simple argument

$$M_{\text{gas}}(r_{\text{vir}}) + M_{\text{star}}(r_{\text{vir}}) = f_b M_{\text{vir}}. \tag{16}$$

Once the equation of state (equation [15]) and the saturated configuration (equation [16]) are specified, we can obtain the newly established gas distribution by solving the following

equations:

$$\frac{dP_e}{dr} = -\frac{GM_{DM}(r)}{r^2}\mu m_p \left(\frac{P_e}{kT}\right);$$ (17)

$$\frac{dM_{\text{gas}}}{dr} = 4\pi\mu_e m_p r^2 \left(\frac{P_e}{kT}\right),$$ (18)

in which $P_e = n_e kT$. The resulting gas density, temperature and entropy distributions are shown in Figure 2 - Figure 4 for various temperatures ranging from 0.5 keV to 14 keV. It appears that both the cores in the gas density profiles and the entropy floors are created in the centers as a result of galaxy formation which has consumed the central gas by converting it into stars. The effect is more significant in lower temperature systems than in higher ones, as was naturally expected. On the other hand, the conservation of entropy during the formation of galaxies leads to a remarkable increase of the gas temperature towards the centers of groups/clusters. Although radiative cooling has not been included in the above treatment, the significantly raised gas temperature in the central regions can help to increase the cooling time which scales as $T^{1/2}$. It thus remains to be an interesting issue of whether the combined effect can resolve or release the cooling flow crisis claimed by a number of recent observations with *Chandra* and *XMM* (e.g. Fabian et al. 2001). For the latter, the most compelling evidence comes from the X-ray spectra obtained towards the central regions in clusters which show a remarkable lack of emission lines from gas with $T < 1$ keV (Peterson et al. 2001). One of the suggested mechanisms is that there is an additional transport mechanism that can reheat the cool gas back to the hot phase. In this regard, the formation of galaxies in the central regions which simultaneously raises the temperature of the gas may serve as a natural heating mechanism. Of course, further work should be done to test this speculation.

EDITOR: PLACE FIGURE 2 HERE.

EDITOR: PLACE FIGURE 3 HERE.

EDITOR: PLACE FIGURE 4 HERE.

3. Comparison to observations

3.1. Radial distribution of gas fraction

Within the framework of the GG model a significant amount of gas in the central regions was converted into galaxies. This would inevitably lead to an increasing gas fraction f_{gas} with group/cluster radius, which should be directly testable by current X-ray observations. For this purpose, we first extract a sample of 163 clusters, which contain 176 data points of f_{gas} measured at different radii, from an X-ray image deprojection analysis made by White, Jones & Forman (1997). Note that for some of the clusters the X-ray temperatures T were estimated by the empirical velocity dispersion-temperature correlation. The data points are now divided into three subsamples according to temperature, which contain 42 ($T > 6$ keV, $\langle T \rangle = 7.99$ keV), 98 (3 keV $\leq T \leq 6$ keV, $\langle T \rangle = 4.32$ keV) and 36 ($T < 3$ keV, $\langle T \rangle = 2.36$ keV) clusters, respectively, and each subsample is properly binned for illustrative purpose. In Figure 5 the radial variations of the observed f_{gas} are compared with the predictions for three choices of $T = 8$, 4.3 and 2.4 keV. Next, we choose the two group samples of Mulchaey et at. (1996) and Hwang et al. (1999) used in the construction of the f_{star}-T relation (see equation [1]) to demonstrate the radial variation of the gas fraction in low-temperature systems. These two samples contain 21 groups with temperature ranging from 0.69 keV to 3.38 keV, and the mean temperature is $\langle T \rangle = 1.32$ keV. The binned data are displayed in Figure 5. It is immediately clear from Figure 5 that there is a fairly good agreement between the model predictions and the observations. The

lowest temperature subsample ($\langle T \rangle$ = 2.36 keV) of White et al. (1997) is an exception, exhibiting a somewhat lower amplitude than the theoretical expectation. Perhaps, this can be regarded as the most natural explanation of the monotonically increasing gas fraction with radius seen in many X-ray clusters although a detailed analysis should be made for each individual case.

EDITOR: PLACE FIGURE 5 HERE.

3.2. X-ray surface brightness profile: slope and core radius

The X-ray surface brightness profile $S_{\text{x}}(r)$ can be computed straightforwardly in terms of

$$S_{\text{x}}(r) = \frac{1}{2\pi(1+z)^4} \int_r^{r_{\text{vir}}} \epsilon(T, n_e) \frac{R dR}{\sqrt{R^2 - r^2}}, \tag{19}$$

where z is the cluster redshift, and $\epsilon(T, n_e)$ is the emissivity which is computed by the Raymond & Smith (1977) model with a metallicity of $Z = 0.3 Z_\odot$. The resulting $S_{\text{x}}(r)$ in the 0.5-2.0 keV band for nearby clusters ($z = 0$) are plotted in Figure 6 for a set of 11 groups/clusters with temperatures ranging from 0.5 to 14 keV. It appears that the overall X-ray surface brightness profiles resemble the conventional β model in shape. In order to facilitate a comparison with the existing X-ray imaging measurements of groups/clusters, we fit the predicted X-ray surface brightness profiles to the β model characterized by $S_{\text{x}}(r)/S_{\text{x}}(0) = (1 + r^2/r_c^2)^{(-3\beta+1/2)}$, and work out the slope and core radius parameters, β and r_c. Since the determinations of β and r_c depend somewhat on the extension of the X-ray surface brightness profile if the the available data extend only out to two or three times the core radius, we truncate each $S_{\text{x}}(r)$ at the maximum radii set by the X-ray surface brightness limits $S_{\text{limit}} = 2 \times 10^{-14}$ erg s^{-1} arcmin^{-2} cm^{-2} and $S_{\text{limit}} = 2 \times 10^{-15}$ erg s^{-1} arcmin^{-2} cm^{-2} in the 0.5-2.0 keV band, respectively. These two values have approximately

covered the *ROSAT* limits used in current observations of clusters (e.g. MME). It turns out that all the predicted X-ray surface brightness profiles can be nicely fitted by the β model, and the best-fit β and r_c values for the two flux limits and different choices of redshifts are plotted against the X-ray temperature in Figure 7 and Figure 8, respectively.

EDITOR: PLACE FIGURE 6 HERE.

EDITOR: PLACE FIGURE 7 HERE.

EDITOR: PLACE FIGURE 8 HERE.

For a comparison with real observations, we extract a sample of 93 clusters and 36 groups from the literature in which the best-fit β and r_c values are explicitly provided. The major sources of references include: for clusters, Rizza et al. (1998), EF, MME, Arnaud & Evrard (1999), Neumannn & Arnaud (1999), Vikhlinin, Forman & Jones (1999) and Jones & Forman (1999); for groups, Mulchaey et al. (1996), Dahlem & Thiering (2000), Helsdon & Ponman (2000) and Takahashi et al. (2000). In most cases, the fittings were performed by excluding the central cooling components, which is compatible with our model without the inclusion of the radiative cooling. The corresponding spectral temperature data are taken from the compilation of Wu et al. (1999) and Xue & Wu (2000).

The theoretically predicted and observationally determined slope and core radius parameters for different X-ray temperatures are compared in Figure 7 and Figure 8, respectively. Regardless of the large dispersion in the observationally determined β and r_c especially for groups, the trend of the slowly increasing β and r_c with T is clearly seen, which is consistent with our predictions. In particular, the predicted slope parameter varies

from $\beta \approx 0.3$ for groups to $\beta \approx 0.9$ for very rich clusters, in excellent agreement with current observations. It should be pointed out that the trend towards shallowed surface brightness profiles in low-temperature systems can be attributed to an observational selection effect rather than a property intrinsic to groups/clusters. This can be clearly seen from the overall predicted X-ray surface brightness profiles for systems with different virial masses. Such a property differs significantly from the preheating model in which the flattening of the S_x occurs in a low-temperature system because the preheated gas becomes harder to be trapped in the shallow gravitational potential well (see Cavaliere et al. 1997). We have also plotted in Figure 7 the slope parameters expected in two extreme situations for comparison (cf. Appendix): (1)The isothermal model in which the gas is driven by purely gravitational shocks and (2) the isentropic model in which the gas is preheated and then collapses adiabatically into groups/clusters. The former may correspond to rich clusters, while the latter may be applied to groups under the preheating hypothesis. These two extreme cases give approximately rise to the upper and lower bounds to the β values.

Whether the increasing slope parameters β of X-ray surface brightness profiles from groups to cluster seen in current observations is purely an observational selection effect or a property intrinsic to groups/clusters constitutes a crucial test for the GG model. There are at least two major uncertainties in the current β model fits of the X-ray surface brightness profiles of groups: Firstly, for most groups a single β model does not provide an adequate description of the observed data, and the fit quality depends sensitively on the modeling of central galaxies, cooling flows or AGNs (e.g. Helsdon & Ponman 2000); Secondly, the X-ray emission of most groups remains undetectable outside radii of typically ~ 200–400 kpc due to the limitation of current detector sensitivity (e.g. Ponman et al. 1996; Mulchaey et al. 1996; Helsdon & Ponman 2000), while the virial radii of galaxy groups with temperature $T \approx 1$ keV are about 1 Mpc. It seems that current X-ray observations have only probed the central regions other than the whole groups. It is hoped that the high sensitivity

measurements with the *Chandra* X-ray Observatory can provide a robust constraint on the slopes of X-ray surface brightness profiles for groups and poor clusters especially at large radii.

3.3. X-ray luminosity - temperature relation

We now come to the global properties of groups and clusters. The first test that Bryan (2000) chose for the GG model is the X-ray luminosity-temperature relation. While the predicted $L_{\rm x}$-T relation is essentially consistent with the observed data on cluster scales, there is an apparent disagreement below $T \approx 1$ keV. This could be due to the small sample of poor clusters and groups and/or the observational selection effect of the finite spatial extensions of X-ray emission set by the X-ray flux-limited surveys. For the latter possibility, we recall that the correction for lost flux falling out the detection aperture has been already made in the computation of $L_{\rm x}$ for clusters. The situation for the groups with $\beta \leq 1/2$ is complicated. In most cases, no aperture correction is made in order to avoid the divergence of total X-ray luminosity (e.g. Ponman et al. 1996; Helsdon & Ponman 2000). It is thus possible that the X-ray luminosity excess on group scales predicted by Bryan (2000) can be reduced simply by excluding the X-ray emission outside the detection aperture implied by the flux limit $S_{\rm limit}$. We now re-examine the $L_{\rm x}$-T relation using the catalog of X-ray groups and clusters compiled by Wu et al. (1999) and Xue & Wu (2000). The updated catalog contains 57 groups and 192 clusters whose X-ray temperatures and luminosities are both available. Furthermore, we only account for the X-ray emission within the apertures set by the X-ray surface brightness limits $S_{\rm limit} = 2 \times 10^{-14}$ erg s^{-1} arcmin^{-2} cm^{-2} and $S_{\rm limit} = 2 \times 10^{-15}$ erg s^{-1} arcmin^{-2} cm^{-2} in the 0.5-2.0 keV band, respectively. It appears that the evaluation of the total X-ray luminosity of clusters is almost unaffected by these aperture limits because the corresponding cutoff radii are close to or beyond the virial

radii. For the latter, we simply truncate the clusters at their virial radii. Again, we use the Raymond & Smith (1977) model with a metallicity of $Z = 0.3Z_\odot$ to calculate the X-ray luminosity and plot the resulting L_x-T relation in Figure 9. It turns out that the model matches nicely the observed data over entire temperature range.

EDITOR: PLACE FIGURE 9 HERE.

3.4. Entropy distribution

The last check is the distribution of the central entropy S measured at $0.1r_{200}$ against the X-ray temperature. We use the updated measurements of $S(0.1r_{\mathrm{vir}})$ by Ponman et al. (1999), Lloyd-Davies, Ponman & Cannon (2000) and Xu, Jin & Wu (2001), which contain 67 data points ranging from $T \approx 0.5$ keV to $T \approx 14$ keV. We demonstrate the predicted and measured $S(0.1r_{\mathrm{vir}})$ in Figure 10, which reinforces the finding of Bryan (2000) that the predicted S-T is consistent with the observed one. A larger sample especially at low temperature end will be needed for a critical test of the model prediction.

EDITOR: PLACE FIGURE 10 HERE.

4. Discussion and conclusions

Using various large data sources of X-ray groups and clusters in the literature, we have made an extensive examination of the properties of the galaxy formation-regulated gas evolution model in groups and clusters, proposed recently by Bryan (2000) as an alternative explanation of the entropy excess and the steepening of the X-ray luminosity-temperature

relation in groups and clusters. This model is based on one empirical correlation between the stellar mass fraction f_{star} and temperature T and one hypothesis that the lowest entropy gas in the central regions of groups and clusters was converted into stars. The reliability of the f_{star}-T relation has been justified by other observational facts such as the increasing ratio of gas mass to stellar mass with the X-ray temperature (David et al. 1990), the increasing gas fraction with the X-ray temperature (Figure 1) and the positive correlation between the mass-to-light ratio and the optical luminosity in clusters (Girardi et al. 2000). This suggests a simple scenario that galaxy formation was less efficient in rich clusters than in poor clusters and groups. As for the working hypothesis, the formation of galaxies in the central regions of groups and clusters consumed the central gas and created a gas cavity, which acts as a trigger for an inward gas flow or diffusion. As a consequence, the flat gas core and entropy floor developed in the centers, together with an increasing gas fraction with radius. These predictions are in quantitative agreement with the internal structures of intragroup/intracluster gas revealed by current X-ray observations such as the slope and core distributions characterized by the conventional β model, the radial variations of the gas mass fraction, and the central entropy distributions measured at $0.1r_{200}$. Another success of the model is the reproduction of the X-ray luminosity-temperature relation over a broad temperature range from $T \approx 0.5$ keV to $T \approx 20$ keV. Overall, it seems that this simple model without additional heating can satisfactorily account for the existing X-ray observations.

While both the GG model proposed by Bryan (2000) without additional heating and the prevailing preheating model can equally explain the current X-ray observations, there are a number of essential differences which can be used to distinguish between the two scenarios. For example, the GG model admits the universality of the baryon fraction from groups to rich clusters, while in the preheating scenario the baryon fraction increases with temperature because a considerable amount of gas may still reside outside of the virial radii

as a result of preheating especially in poor clusters and groups. A precise measurement of the total baryon (stars + gas) fractions in groups and clusters can provide a critical test for the models. Alternatively, the X-ray imaging measurements of the surface brightness profiles of poor clusters and groups are probably the simplest way to disentangle the issue: the GG model predicts that the slope of the X-ray surface brightness profile at large radii remains roughly unchanged from groups to clusters, and the increasing slope with temperature seen in current X-ray observations is purely selection effect due to the limitation of detector sensitivity and background noise. On the contrary, within the framework of the preheating scenario the X-ray surface brightness profiles are intrinsically shallower in groups and poor clusters than in rich clusters, insensitive to observational sensitivity. The high sensitivity X-ray observations of groups with advanced detectors like *Chandra* should be able to set robust constraints on the slope parameters of the X-ray surface brightness profiles in the outer regions of groups.

Apparently, the GG model still has its own problems that need to be resolved in the future. First, aside from the robustness problem of the empirical relation between stellar mass fraction and X-ray temperature established based on a small sample of local groups and clusters, it is unclear as to how this relation evolves with redshift. The cosmological applications are largely limited if evolutionary effect is not incorporated into the present model. It is unlikely that there is a significant evolution of groups and clusters since $z \sim 1$ if the inward gas flow or diffusion due to galaxy formation in the central regions ended at the early phase of structure formation. Of course, this depends on how fast the process of inward gas flow or diffusion may take. A related question is: Can one actually observe the process at high-redshift groups and clusters ? Second, the current f_{star}-T relation indicates that nearly all the gaseous materials in less massive groups and giant galaxies have been converted into stars. If this occurred in the early stage of structure formation, there would be no gas left in small systems. How can one explain the existence of a considerably large

fraction of hot gas in clusters if they formed by gravitational aggregation of individual low-mass objects ? One possibility is that the formation of galaxies and the inward gas flow or diffusion in less massive systems proceeded rather slowly and a large fraction of gas had not been converted into stars before they merged with other massive objects. The latter process can raise the gas temperature and thus reduce the efficiency of galaxy formation, according to the $f_{\rm star}$-T relation. A sophisticated analysis incorporated with the halo merger rates described by the extended Press-Schechter formalism (Lacey & Cole 1993) may be needed to clarify the issue. Third, the GG model predicts that the temperature profile shows a dramatic increase towards the centers and a significant decline at large radii. Although the inclusion of radiative cooling is expected to reduce somewhat the central X-ray temperature, whether or not this can yield a quantitative agreement with X-ray spectral analysis remains unclear. It is also interesting to explore the possibility of whether or not such a rising temperature towards the centers of clusters can alleviate the cooling flow crisis. Finally, it is worth mentioning that the overall radiative cooling may play an important role in the removal of low-entropy gas in the centers of groups and clusters, giving rise to an equally good explanation of the steepening of the $L_{\rm x}$-T relation for groups and clusters (Muanwong et al. 2001).

Overall, the GG model has seemingly proved very successful at explaining a number of internal and global properties of the intragroup/intracluster gas. If confirmed, this would have profound implications for our understanding of the origin and distribution of the intragroup/intracluster gas, the formation history of group/cluster galaxies, the missing baryons in the universe, and even the formation and evolution of structures in the universe.

In this Appendix we discuss the gas distributions in two extreme cases: the isothermal and isentropic models. The former may work in rich clusters where the gas was mainly heated by gravitational shocks, while the latter may correspond to the intragroup gas which was preheated and then collapsed adiabatically into the gravitational potential wells of the groups. A detailed discussion about the X-ray luminosity-temperature relations in the two models can be found in Balogh et al. (1999). Here, we concentrate on the radial gas density profiles and use a new prescription suggested recently by Eke, Navarro & Steinmetz (2001) for the assignment of the collapse redshift of dark halos. Again, we adopt the NFW profile for a virialized dark halo, and determine its virial temperature in terms of equation (4). In order to fix the free parameters, δ_c or r_s or c in the NFW profile. The collapse redshift z_{coll} for each halo identified at $z = 0$ is introduced through (Eke et al. 2001)

$$D(z_{coll})\sigma_{eff}(M_s) = \frac{1}{C_\sigma},\qquad(1)$$

where $C_\sigma \approx 25$ for the ΛCDM model, D is the normalized linear grow factor, for which we take the approximate expression from Carroll, Press & Turner (1992), $\sigma_{eff}(M_s)$ is the so-called modulated rms linear density at mass scale M_s:

$$\sigma_{eff}(M_s) \equiv \sigma(M_s)\left[-\frac{d\ln\sigma(M_s)}{d\ln M_s}\right],\qquad(2)$$

and M_s is defined as the mass contained within $r_{max} = 2.17 r_s$ where the circular velocity reaches its maximum and

$$M_s = \frac{0.47M}{\ln(1+c) - c/(1+c)}.\qquad(3)$$

We adopt the following parameterization of the power-spectrum of initial fluctuation

$$P(k) = A\,k^n\,T^2_{CDM}(k),\qquad(4)$$

where n is the primordial power spectrum and is assumed to be the Harrison-Zeldovich case $n = 1$, and $T_{CDM}(k)$ is the transfer function of adiabatic CDM model for which we use the

fit given by Bardeen et al. (1986):

$$T_{\mathrm{CDM}}(q) = \frac{\ln(1 + 2.34q)}{2.34q}[1 + 3.89q + (16.1q^2) + (5.46q)^3 + (6.71q)^4]^{-1/4}, \qquad (5)$$

where $q = (k/h\ \mathrm{Mpc}^{-1})/\Gamma$, and $\Gamma = \Omega_{\mathrm{M}}h\exp[-\Omega_{\mathrm{b}}(1 + \sqrt{2h}/\Omega_{\mathrm{M}})]$ is the shape parameter. Once a power spectrum, $P(k)$, is specified, the mass variance becomes

$$\sigma^2(M) = \frac{1}{2\pi^2}\int_0^\infty k^2 P(k)W^2(kR)dk, \qquad (6)$$

in which $W(x) = 3(\sin x - x\cos x)/x^3$ is the Fourier representation of the window function. The amplitude A in the power spectrum is determined using the rms mass fluctuation on an 8 h^{-1} Mpc scale, σ_8, for which we take $\sigma_8 = 0.93$ for our ΛCDM model. Finally, the relationship between the NFW profile and its collapse reshift z_{coll} is established if we define a new characteristic density, $\tilde{\rho}_s = 3M_{\mathrm{vir}}/4\pi r_s^3$, and set to equal the spherical collapse top-hat density at z_{coll}:

$$\tilde{\rho}_s = \Delta(z_{\mathrm{zoll}})\rho_{\mathrm{crit}}(z_{\mathrm{coll}}). \qquad (7)$$

I. Isothermal model

We first assume that the hot gas is isothermal with electron number density $n_e(r)$ and temperature T, and is in hydrostatic equilibrium with the underlying gravitational potential dominated by the NFW profile:

$$-\frac{GM_{\mathrm{DM}}(r)}{r^2} = \frac{1}{\mu m_p n_e(r)}\frac{d[kTn_e(r)]}{dr}. \qquad (8)$$

A straightforward computation yields an analytic form of the electron density profile (Makino, Sasaki & Suto 1998)

$$n_e(r) = n_e(0)\frac{(1 + r/r_s)^{\alpha/(r/r_s)} - 1}{e^\alpha - 1}, \qquad (9)$$

where we have adopted the normalized, background-subtracted form in order to ensure the convergence of the X-ray surface brightness, and $\alpha = 4\pi G\mu m_p\delta_c\rho_{\mathrm{crit}}r_s^2/kT$. In terms of the

virial theorem, the α parameter reduces to

$$\alpha = \frac{3c}{\ln(1+c) - c/(1+c)}. \tag{10}$$

Here we have assumed that the specific kinetic energy of dark matter particles is equal to that of gas: $\beta_{\mathrm{spec}} = \sigma^2/(kT_{\mathrm{vir}}/\mu m_p) = 1$. In turns out from the prescription of the dark halo formation discussed above that α is a slowly decreasing function of virial mass or temperature, ranging from 22.5 to 14 for $10^9 M_\odot \leq M \leq 10^{17} M_\odot$. This is in good agreement with the observationally determined values for clusters (e.g. EF; Wu & Xue 2000).

Once the electron density and temperature are specified for different systems, we can calculate the X-ray surface brightness profile using an optically thin, isothermal plasma emission model by Raymond & Smith (1977). Finally, we fit the predicted X-ray surface brightness profile to the β model and work out the best-fit β and r_c parameters. It appears that the resulting β parameter decreases slightly with temperature, as shown in Figure 7. At the high temperature end of $T > 10$ keV, the predicted slope parameter reaches $\beta \sim 0.8 - 0.9$, roughly consistent with observed values for very rich clusters.

II. Isentropic model

The specific entropy of the gas can be conveniently defined as

$$S = \frac{kT}{n_e^{\gamma-1}}, \tag{11}$$

where γ is the polytropic index. In the case of where the gas is accreted adiabatically, $\gamma = 5/3$. We solve the hydrostatic equilibrium equation by demanding that the entropy of the gas is conserved during accretion. We specify such a boundary condition that the electron number density and temperature at large radii should approach asymptotically the background values $n_{e,b}$ and T_b, respectively. We caution that this last constraint may break down beyond virial radius because of the failure of hydrostatic equilibrium. Therefore, this boundary condition should only be taken to be a reasonable approximation. The electron

number density and temperature profiles are

$$n_e(r) = n_{e,b} \left[1 + \alpha_b \left(\frac{\gamma - 1}{\gamma} \right) \frac{\ln(1 + r/r_s)}{r/r_s} \right]^{\frac{1}{\gamma - 1}} ; \tag{12}$$

$$T(r) = T_b \left[1 + \alpha_b \left(\frac{\gamma - 1}{\gamma} \right) \frac{\ln(1 + r/r_s)}{r/r_s} \right], \tag{13}$$

where

$$\alpha_b = \frac{4\pi G \mu m_p \delta_c \rho_{\mathrm{crit}} r_s^2}{kT_b} = \frac{4\pi G \mu m_p \delta_c \rho_{\mathrm{crit}} r_s^2}{S n_{e,b}^{\gamma - 1}}. \tag{14}$$

Nevertheless, we use the background-subtracted electron density $\bar{n}_e(r) = n_e(r) - n_{e,b}$ and temperature $\bar{T}(r) = T(r) - T_b$ to proceed our calculation of the corresponding X-ray emission, i.e.,

$$\frac{\bar{n}_e(r)}{n_{e,b}} = \left\{ \left[1 + \alpha_b \left(\frac{\gamma - 1}{\gamma} \right) \frac{\ln(1 + r/r_s)}{r/r_s} \right]^{\frac{1}{\gamma - 1}} - 1 \right\} ; \tag{15}$$

$$\frac{\bar{T}(r)}{T_b} = \alpha_b \left(\frac{\gamma - 1}{\gamma} \right) \frac{\ln(1 + r/r_s)}{r/r_s}. \tag{16}$$

The key parameter that determines the shape of the X-ray surface brightness profile $S_x(r)$ is α_b. The typical value of α_b in terms of the above evaluations of δ_c and r_s for a given halo M_{vir} or T_{vir} is $\alpha_b \sim 4\pi G \mu m_p \delta_c \rho_{\mathrm{crit}} r_s^2 / kT_{\mathrm{vir}} \sim 10$ for $10^9 M_\odot \leq M \leq 10^{17} M_\odot$. We have numerically obtained the profiles of $S_x(r)$ for a number of α_b and fitted them to the β model over a radius range of $0 \leq r \leq 100 r_s$. The resulting β starts from ~ 0.3 for $\alpha_b = 10$ and approaches ~ 0.4 for the extremely large values of $\alpha_b \sim 10^4$ (see Figure 7). Such a broad range of α_b should cover a broad mass range from groups to rich clusters. It appears that the saturated configuration of the isentropically accreted gas in an NFW-like gravitational potential well looks quite shallow and can be well represented by the conventional β model with $\beta \approx 0.3 - 0.4$.

REFERENCES

Arnaud, M., & Evrard, A. E. 1999, MNRAS, 305, 631

Balogh, M. L., Babul, A., & Patton, D. R. 1999, MNRAS, 307, 463

Bardeen, J. M., Bond, J. R., Kaiser, N., & Szalay, A. S. 1986, ApJ, 304, 15

Bower, R. G., et al. 2001, MNRAS, 325, 497

Bryan, G. L. 2000, ApJ, 544, L1

Bryan, G. L., & Norman, M. L. 1998, ApJ, 495, 80

Carroll, S. M., Press, W. H., & Turner, E. L. 1992, ARA&A, 30, 499

Cavaliere, A., Menci, N., & Tozzi, P. 1997, ApJ, 484, L21

Cavaliere, A., Menci, N., & Tozzi, P. 1999, MNRAS, 308, 599

Dahlem, M., & Thiering, I. 2000, PASP, 112, 148

David, L. P., Arnaud, K. A., Forman, W., & Jones, C. 1990, ApJ, 356, 32

David, L. P., Slyz, A., Jones, C., Forman, W., & Vrtilek, S. D. 1993, ApJ, 412, 479

Edge, A. C., & Stewart, G. C. 1991, MNRAS, 252, 414

Eke, V. R., Navarro, J. F., & Steinmetz, M. 2001, ApJ, 554, 114

Ettori, S., & Fabian, A. C. 1999, MNRAS, 305, 834 (EF)

Fabian, A. C., Mushotzky, R. F., Nulsen, P. E. J., & Peterson, J. R. 2001, MNRAS, 321, L20

Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518

Girardi, M., et al. 2000, ApJ, 530, 62

Helsdon, S. F., & Ponman, T. J. 2000, MNRAS, 315, 356

Henry, J. P., & Arnaud, K. A. 1991, ApJ, 372, 410

Horner, D. J., Mushotzky, R. F., & Scharf, C. A. 1999, ApJ, 520, 78

Hwang, U., Mushotzky, R. F., Burns, J. O., Fukazawa, Y., & White, R. A. 1999, ApJ, 516, 604

Jones, C., & Forman, W. 1999, ApJ, 511, 65

Kaiser, N. 1991, ApJ, 383, 104

Lacey, C., & Cole, S. 1993, MNRAS, 262, 627

Lloyd-Davies, E. J., Ponman, T. J., & Cannon, D. B. 2000, MNRAS, 315, 689

Makino, N., Sasaki, S., & Suto, Y. 1998, ApJ, 497, 555

Mathiesen, B. F., & Evrard, A. E. 2001, ApJ, 546, 100

Mohr, J. J., Mathiesen, B., & Evrard, A. E. 1999, ApJ, 517, 627 (MME)

Muanwong, O., Thomas, P. A., Kay, T., Pearce, F. R., & Couchman, H. M. P. 2001, ApJ, 552, L27

Mulchaey, J. S., Davis, D. S., Mushotzky, R. F., & Burstein, D. 1996, ApJ, 456, 80

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1995, MNRAS, 275, 720 (NFW)

Neumann, D. M., & Arnaud, M. 1999, A&A, 348, 711

Peterson, J. R., et al. 2001, A&A, 365, L104

Ponman, T. J., Bourner, P. D. J., Ebeling, H., & Böhringer, H. 1996, MNRAS, 283, 690

Ponman, T. J., Cannon, D. B., & Navarro, J. F. 1999, Nature, 397, 135

Raymond, J. C., & Smith, B. W. 1977, ApJS, 35, 419

Rizza, E., et al. 1998, MNRAS, 301, 328

Takahashi, I., et al. 2000, PASJ, 52, 769

Vikhlinin, A., Forman, W., & Jones, C. 1999, ApJ, 525, 47

White, D. A., Jones, C., & Forman, W. 1997, MNRAS, 292, 419

Wu, K. K. S., Fabian, A. C., & Nulsen, P. E. J. 2000, MNRAS, 2000, 318, 889

Wu, X.-P., & Xue, Y.-J. 2000, ApJ, 542, 578

Wu, X.-P., Xue, Y.-J., & Fang, L.-Z. 1999, ApJ, 524, 22

Xu, H.-G., Jin, G.-X., & Wu, X.-P. 2001, ApJ, 553, 78

Xue, Y.-J., & Wu, X.-P. 2000, ApJ, 538, 65

Fig. 1.— Gas mass fraction within r_{500} versus X-ray temperature for nearby rich clusters. A total of 55 clusters from Mohr et al. (1999; MME) and Ettori & Fabian (1999; EF) are shown. Also plotted are the expectations from the correlations between the stellar mass fraction and X-ray temperature given by Bryan (2000) (solid line) and between the virial mass and optical luminosity found by Girardi et al. (2000) (dotted line), in combination with the universality of the total baryon fraction in clusters predicted by the Big Bang Nucleosynthesis (BBN) (dashed line).

Fig. 2.— Normalized gas density profiles for different X-ray temperatures ranging from 0.5 keV to 14 keV. The initial profiles and the galaxy formation-regulated gas distributions are plotted by dotted and solid lines, respectively.

Fig. 3.— The same as Figure 2 but for the true temperature profiles.

Fig. 4.— The same as Figure 2 but for the entropy profiles.

Fig. 5.— Radial variations of the gas mass fraction. The predicted profiles (dotted lines, from top to bottom) correspond to four different choices of temperatures $T = 8.0$, 4.3, 2.4 and 1.3 keV. Also shown are the observationally derived 176 data points of clusters (open symbols) by White et al. (1997) and 21 data points of groups (filled stars) by Mulchaey et al. (1996) and Hwang et al. (1999) within different radii, which are properly binned according to temperature and radius.

Fig. 6.— The predicted X-ray surface brightness profiles in the 0.5-2.0 keV band for a set of 11 groups/clusters with temperatures ranging from 0.5 to 14 keV (from bottom to top). Dotted lines correspond to the X-ray surface brightness limits $S_{\text{limit}} = 2 \times 10^{-14}$ erg s^{-1} arcmin^{-2} cm^{-2} (upper) and $S_{\text{limit}} = 2 \times 10^{-15}$ erg s^{-1} arcmin^{-2} cm^{-2} (lower), respectively.

Fig. 7.— Dependence of the slope parameter (β) upon X-ray temperature (T). A total of

127 groups and clusters extracted from the literature are shown. Thick and thin solid lines are the best-fit β values from the GG model with and without the correction for maximum detectable radius, among which the three thick solid lines from top to bottom correspond to $(S_{\mathrm{limit}}, z)= (2 \times 10^{-14}$ erg s^{-1} arcmin^{-2} cm^{-2}, 0$)$, $(2 \times 10^{-15}$ erg s^{-1} arcmin^{-2} cm^{-2}, 0$)$, and $(2 \times 10^{-15}$ erg s^{-1} arcmin^{-2} cm^{-2}, 0.2$)$, respectively. Dashed line is the best-fit value from the isothermal model. Dotted lines represent the results in the isentropic model for α_b ranging from 10 to 10^4, which covers a broad mass range from groups to rich clusters (see Appendix).

Fig. 8.— Comparison of the theoretically predicted core radii and the best-fit values from X-ray observations for different temperatures. Virial theorem is used to assign r_{200} to each group/cluster. Thick and thin lines correspond to the β model fittings with and without the correction for maximum detectable radius. The notations are the same as in Figure 7.

Fig. 9.— Comparison of the predicted bolometric X-ray luminosity-temperature relation and the observed data. A total of 57 groups and 192 clusters with available T and L_{x} in the literature are shown. The upper and lower lines correspond to the two flux limits shown in Figure 6, $S_{\mathrm{limit}} = 2 \times 10^{-14}$ erg s^{-1} arcmin^{-2} cm^{-2} and $S_{\mathrm{limit}} = 2 \times 10^{-15}$ erg s^{-1} arcmin^{-2} cm^{-2}, respectively.

Fig. 10.— Dependence of the central gas entropy measured at $0.1r_{200}$ upon the X-ray temperature. The model prediction is plotted by solid line. The observational results from Ponman et al. (1999; PCN), Lloyd-Davies et al. (2000; LPC) and Xu et al. (2001; XJW) are clearly marked.

Cosmology: $\Omega_M=0.3$ $\Omega_b=0.076$ $h=0.65$

BBN

$f_{gas}(r_{500})$

0.4

0.1

1

10

T (keV)

55 clusters   [MME(•):42 + EF(□):13] at z<0.1